

## **MIDDLE EAST AND NORTH AFRICA DATABASE DEVELOPMENT AND RESEARCH TO POPULATE THE DOE KNOWLEDGE BASE**

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### **ABSTRACT**

The objective of this work is to update, analyze, and document data for the Middle East and North Africa regions in order to provide accurate input to the DOE's Knowledge Base system. Specifically, we aim to provide assessments and comparison of different geophysical databases, such as Moho and basement maps, for the region of study, in an effort to document the accuracy and the extent and magnitude of the discrepancies. Additional "ground truth" information, primarily based on satellite information, for distinguishing mine-related activity are also to be provided, both through analysis of existing data at Cornell, and where possible, through in-country sources. Another objective is to map characteristics of regional seismic wave propagation and to document velocity models for the Middle East using data available to Cornell University.

To date, we have developed and delivered to DOE authorities (1) a complete crustal structure including detailed topography, sediment thickness, and Moho depth values for the entire Middle East and North Africa regions, (2) our regional seismic waveform attenuation characteristics results in the Middle East region, and (3) a comprehensive study of Moho and basement depth models for the region.

We developed a new complete crustal model for the Middle East and North Africa regions. The final model includes topography, basement depth, and Moho depth values for the entire region. These models are justifiable and better represent the crustal structure in the Middle East and North Africa regions. These models will serve as a good starting point in geophysical studies in this region. We also conducted a comparative study of available Moho and basement data sets developed by different groups in these regions.

We also determined the regional seismic wave (Sn and Lg) attenuation characteristics using a ratioing technique. We obtained tomographic images of efficient and inefficient Lg and Sn phases using data from local seismic networks in the region. We specifically utilized waveform data from the Turkish National Seismic Network, Syrian National Seismic Network, and all available permanent and temporary broadband stations in these regions.

Our future work will include developing a detailed tomographic upper mantle velocity images in the region. We will modify and improve existing Pn velocity models in the region by making use of local station data and readings.

**Key Words:** Databases, Moho, basement, Middle East, North Africa, GIS, CTBT

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## **OBJECTIVE**

The objective of this work is to update, analyze, and document data for the Middle East and North Africa in order to provide accurate input to the DOE Knowledge Base system. Specifically, we aim to provide assessments and comparison of different geophysical databases, such as Moho and basement maps, for the region of study, in an effort to document the accuracy and the extent and magnitude of the discrepancies. Additional “ground truth” information, primarily based on satellite information, for distinguishing mine-related activity are also to be provided, both through analysis of existing data at Cornell, and where possible, through in-country sources. Another objective is to map characteristics of regional seismic wave propagation and to document velocity models for the Middle East using data available to Cornell University. We will also provide metadata and the appropriate references for the above work.

The work under this Cooperative Agreement is being coordinated with scientists at the Lawrence Livermore National Laboratory (LLNL) and the Sandia National Laboratory (SNL).

## **RESEARCH ACCOMPLISHED**

### **A. MIDDLE EAST AND NORTH AFRICA CRUSTAL STRUCTURE**

Currently, there are several data sets that provide information about the crustal structure in the Middle East and North Africa regions. These data sets vary in quality and resolution. Utilization of these data sets in seismological research efforts will likely produce different results. In order to determine and document variations in data sets for a given region we analyzed each data set individually and then calculated differences and determined statistical correlations among data sets. All data were entered into ArcInfo GIS software and processed using the surface processing tools provided in that software.

We have analyzed the following data sets: Cornell Moho, LLNL Moho, CRUST 5.1, IPE Moho, Cornell basement, LLNL basement, UC basement, CRUST 5.1 basement, IPE basement.

#### **A.1. Moho Data Sets**

##### ***- Cornell University Moho Map***

The Cornell University Moho map was developed by us over several years (Figure 1). The data set covers a significant portion of the Middle East and North Africa region. It was compiled from several different data sources. These sources include crustal scale refraction and reflection profiles, receiver function depth estimations, gravity modeling, and surface wave dispersion curve inversion results.

The majority of the Middle East data sets were compiled from about 50 refraction and gravity profiles in the region. The complete set of profiles and their interpretations are available in our web site at <http://atlas.geo.cornell.edu/htmls/fin2/figmain.html>. We digitized all these crustal cross section interpretations and marked the basement and Moho interfaces in each cross section. We also used the receiver function results from our previous seismological studies in the region (e.g., Sandvol et al., 1998a; Sandvol et al., 1998b). Later, we used them in the interpolation to obtain a gridded Moho map for the region.

Several contour maps were also digitized to provide constraints in the gridding. We collected contour maps for Iran, Afar triangle, Egypt, Aegean Sea, Greece, Italy, and the eastern Mediterranean Sea (see refs). In addition, some Moho values were digitized from interpretations of low resolution refraction profiles with PmP measurements as points for North Africa.

Collectively, these data sets were used to obtain the Cornell University Moho map for the region. In order to provide constraining points in regions with sparse data coverage, we added pseudo Moho depth values based on known tectonic units. Using 3 km resolution bathymetry maps we outlined the edge of the continental shelf and assigned a Moho thickness of 15 km to these contours. The 15 km Moho depth was chosen arbitrarily to approximate the crustal thinning from the continental regions to oceanic regions. We also added pseudo contours in inland areas of the continents to allow a rapid transition to continental Moho depth just after the shelf margin.

#### **-LLNL MENA 1.0 Moho Map**

The MENA 1.0 crustal model of Sweeney and Walter (1998) is a modified version of the CRUST 5.1 velocity model. The details of the models are provided in the mentioned report and will not be discussed here in detail. However, it is important to note that this model is a regionalized model. The entire region is divided into 28 distinct tectonic units, and each tectonic unit is assigned a uniform crustal thickness and velocity structure. These values are mainly adopted from the CRUST 5.1 global model with some modifications.

#### **-IPE Moho Map**

The IPE Moho map actually covers all of Eurasia. The coverage in the Middle East and North Africa, however, is not complete. The data set covers the region from about 24.5N to north. For this reason, it is not possible to make a full comparison with other data sets.

This data set is also the least known among the Moho maps. The depth-to-Moho contour maps published by the Soviet IPE (Institute for the Physics of the Earth) were digitized by the Cornell group, and a gridded map was obtained. However, the accuracy of the contours is not known. It is speculated that the contours were based on interpretations of refraction, gravity, and surface wave studies in the region. Currently, there is no information available about the data sampling and resolution. However, the contour values, at continental scales, are consistent with known crustal thicknesses in the region. At larger scales this correlation is lost, indicating that data used in contouring were sparse.

#### **-CRUST 5.1 Moho**

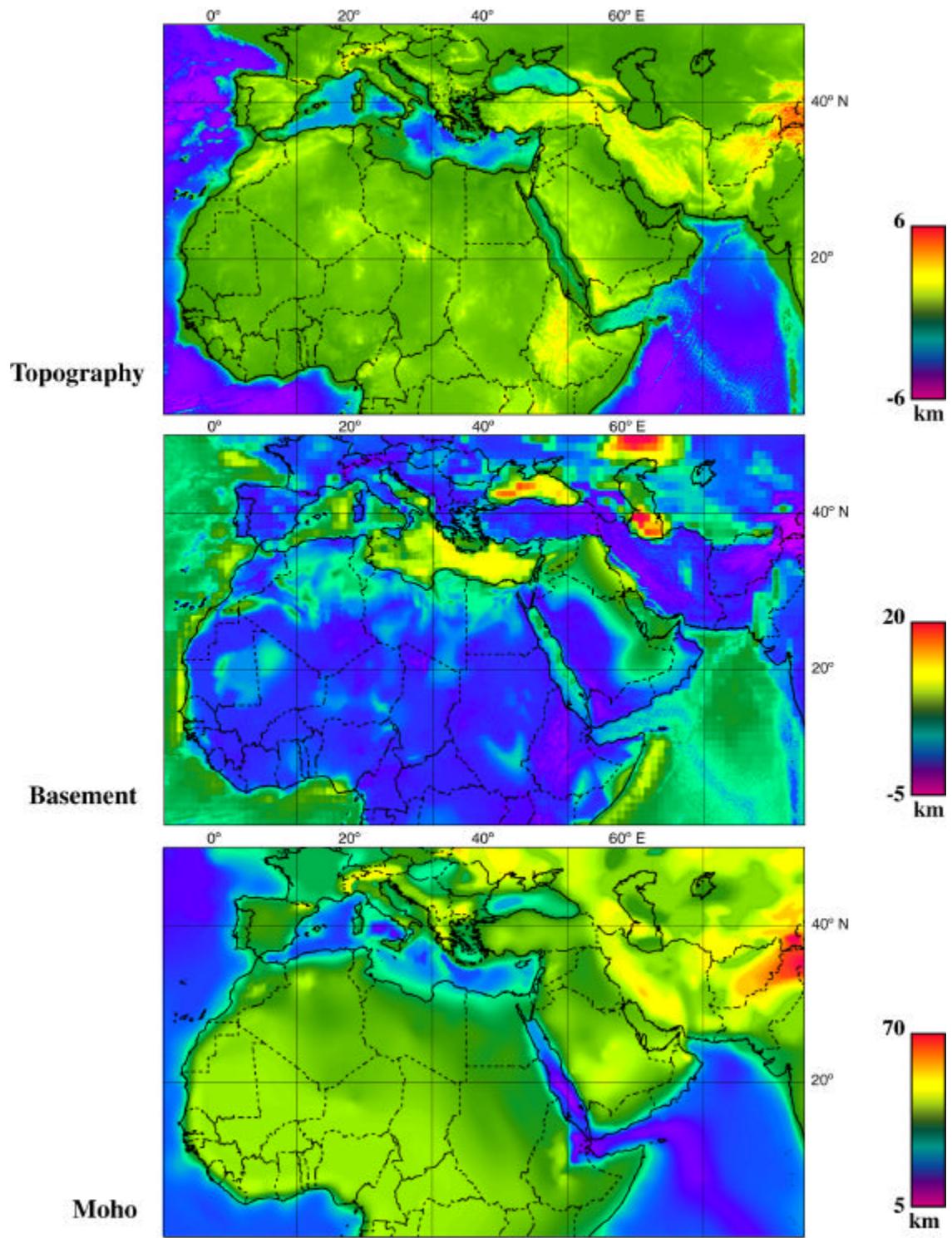
The CRUST 5.1 model is a global data set with 5x5 degree resolution (Mooney et al., 1998). The biggest disadvantage of this model is its low resolution. Areas more than 500 km in width and length are assigned only one average value. However, the model also consists of velocities that could help in forming a complete crustal structure. The details of this model are described in Mooney et al. (1998) and will not be discussed here.

### **A. 2. Comparisons of Moho data sets**

All these Moho data sets were imported into ArcInfo software and calculations were done within the ArcInfo environment. We gridded all data to 10 km cell size, even though none of the data sets has 10 km resolution. To determine how these four different Moho data sets compare with each other, we calculated the correlation matrix for the four data sets.

**Table 1.** Correlation Matrix for Moho Data Sets

	<b>Cornell</b>	<b>MENA 1.0</b>	<b>IPE</b>	<b>CRUST 5.1</b>
<b>Cornell</b>	1.00000	0.67289	0.51157	0.58360
<b>MENA 1.0</b>	0.67289	1.00000	0.63023	0.79576
<b>IPE</b>	0.51157	0.63023	1.00000	0.58733
<b>CRUST 5.1</b>	0.58360	0.79576	0.58733	1.00000



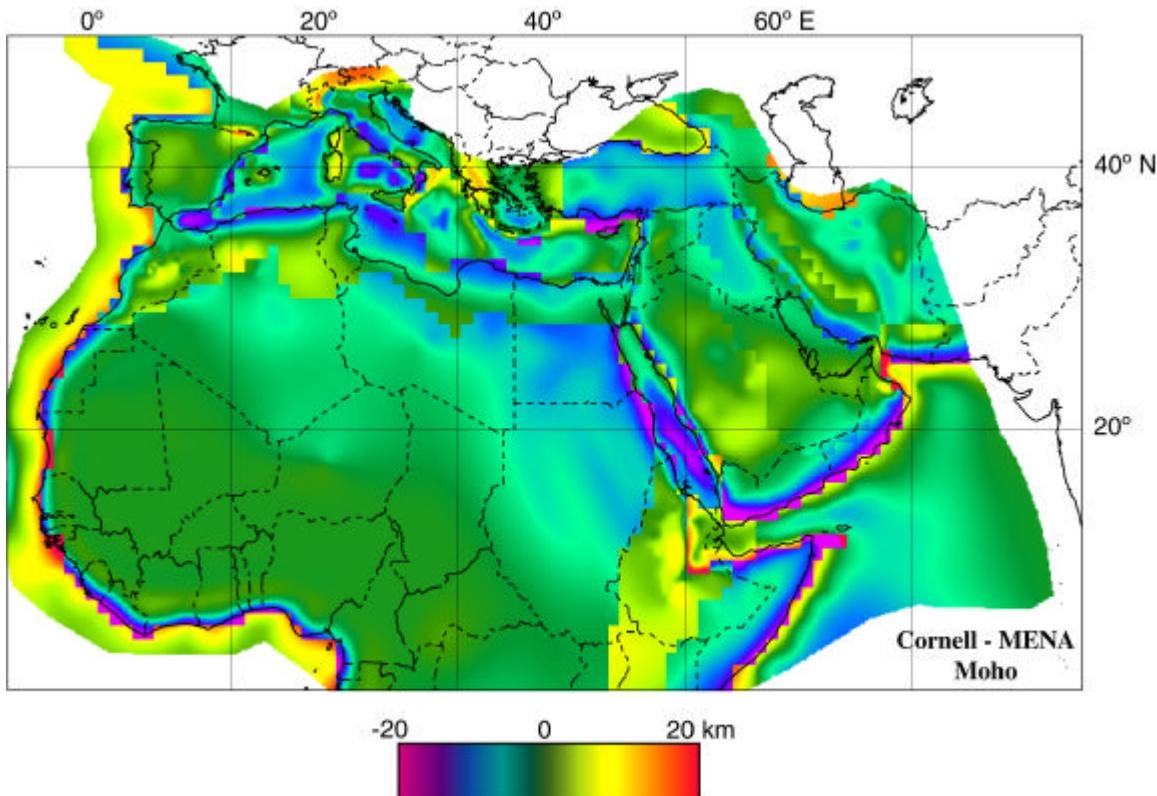
**Figure 1.** Maps showing the final crustal structure for the Middle East and North Africa region. Cornell basement and Moho depth data sets represent the best known structure for the Middle East and North.

### **Cornell Moho vs MENA 1.0**

The differences between the two data sets are at relatively short length scales (Figure 2). This is expected because of the nature of the MENA 1.0 data set. Since this data set is generalized, and the Moho depth varies within a tectonic unit, most of the differences reflect variations occurring within a tectonic zone identified in the MENA 1.0 model. In a few places such as the Red Sea, the Alps, the Zagros, and the East African rift, longer wavelength variations are observed.

The majority of short wavelength variations are observed near the continental margins where a sudden change in crustal thickness occurs. Since none of the data sets has “measured” depth-to-Moho along the continental margins, these changes are expected and cannot really be constrained. However, there are significant differences in Moho depth values of the two data sets in certain regions, such as the Pyrenees, and beneath the Sardinia and Corsica Islands. These short period, but high magnitude variations are probably due to the generalization process of the MENA 1.0 data set. It is known that the Pyrenees are underlain by thicker crust due to continental subduction. Similarly, the Moho beneath the Corsica and Sardinia Islands is deeper than beneath the adjacent oceanic areas. This is not observed in the MENA 1.0 map.

We believe the longer period variations are also a result of oversimplification of the tectonic boundaries. For example, the large variations in Moho depth along the Red Sea are due to the assumption in the MENA 1.0 data set that the entire Red Sea is underlain by a uniform crustal thickness. However, geophysical and geological studies suggest that the rifting and oceanic spreading in the southern part of the Red Sea is much more mature. The northern Red Sea is still in its early rifting stages and no oceanic crust yet exists there. This along strike variation is reflected in Moho depth as well.



**Figure 2.** Map showing the differences between the Cornell Moho and the MENA 1.0 Moho data sets.

### ***Comparisons of Other Moho Data Sets***

The overlap between the Cornell Moho and the IPE Moho maps is quite limited; only about  $\frac{1}{4}$  of the region is covered by the overlap between the two data sets. The differences in Moho values span a wide range of values, the majority of the variations are in the  $\pm 9$  km range.

The Cornell Moho and the CRUST 5.1 maps also show strong variation in the Middle East and North Africa region. This is an expected phenomenon because of the extremely low resolution of the CRUST 5.1 data set. Very large (up to  $\pm 20$  km) variations exist at the margins of the continents. A 5-degree cell size in the CRUST 5.1 data set does not provide enough resolution to meaningfully analyze the Moho structure in this region.

The MENA 1.0 and the IPE maps overlap in the northern half of the area of interest. The largest variations between the data sets are in Pakistan, Afghanistan, and the southern Caspian Sea. The IPE values in these regions are much larger ( $\sim 10$  km) than the Moho depth values in the MENA 1.0 data set. Additional differences occur along the continental margins, where the resolution of the MENA 1.0 data set plays an important role.

The MENA 1.0 and the CRUST 5.1 model correlate reasonably well since the MENA 1.0 is based on the CRUST 5.1 model, and the differences reflect the modifications made to the CRUST 5.1 model in order to obtain the MENA 1.0 crustal model. More than 30% of the values in the two data sets are within  $\pm 1$  km range.

The mismatches between the CRUST 5.1 and IPE data sets are quite strong. The variations in this case are not limited to continental margins; they are distributed over the entire region. The strong variations to note are in the Bay of Biscay, the Pyrenees, the Alps, the entire Mediterranean basin, northwest Arabia, the Persian Gulf, and the Hindu Kush mountains.

### **A. 3. Basement Data Sets**

#### ***- Cornell University Basement Map***

The basement structure shown in Figure 1 was obtained by merging the Cornell's older version basement map, which covers mostly the land areas in the Middle East and North Africa regions, with the UCSD basement map. The UCSD map is used to supplement the sediment thickness in oceanic areas. We chose the UCSD sediment map for the compilation, because of the good correlation between the two data sets as well as the consistency of models with known tectonic units. In order to account for the topographic and bathymetric changes, we also added the topography/bathymetry data shown in Figure 1 to this basement map. By doing so, we obtained a basement depth data set that includes topography and the water level.

#### ***- LLNL MENA 1.0 Basement Map***

The MENA 1.0 Basement values were extracted from the MENA 1.0 crustal model based on P wave velocity values. A P wave velocity of 6 km/s was selected as the basement identifier in the velocity model. The depth where P wave velocity jumps over 6.0 km/s was taken to represent the basement depth in that region.

This data set is a revised version of the CRUST 5.1 model. The details of these data are described in Sweeney and Walter (1998). The model has 28 different tectonic units, and each unit is assigned a unique depth to basement value.

#### ***- IPE Basement Map***

The IPE basement map is similar to the IPE Moho map in its geographic extent, covering only the northern part of the Middle East and North Africa region. This data set was digitized from the Soviet IPE basement map contours. The reliability of the contour values remains as a problem. There is currently no information about how these contours were drawn and what the resolution limits are in this data set. This basement map shows very deep basins in the Caspian Sea, the eastern Mediterranean Sea, and the Black Sea regions. It is known that the southern Caspian Sea is underlain by very thick sedimentary cover (about 20 km).

Similarly, the Black Sea is known to be underlain by a deep basin. For these known areas, the IPE basement values appear consistent with known structures. However, the IPE map also shows zero sediment thickness in most parts of the Middle East where it is known that there are thick sedimentary covers. For example, parts of Morocco, Syria, and Turkey are shown in this map as regions with no sedimentary cover. However, based on recent studies we know that there are several sedimentary basins in these regions.

#### **- University of California Basement Map**

The UC basement map is a compilation from several sources and it provides global sediment thickness estimations at 1x1 degree resolution. The details for this model can be obtained from <http://mahi.ucsd.edu/Gabi/sediment.html>. We cropped the global data set to show only the Middle East and North Africa region. This map also shows the large basins in the regions, such as the southern Caspian, the Black Sea, and the eastern Mediterranean. Smaller size variations in sediment thickness will be less accurate, since the sample size is more than 100 km in this map.

#### **-CRUST 5.1 Basement Map**

Due to extremely large sample spacing, it is almost impossible to evaluate this data set for sediment thickness. Very few tectonic units show distinct sediment thickness values. The Black Sea and parts of the eastern Mediterranean Sea and southern Caspian Sea regions are examples of these units. However, the sampling size precludes a meaningful analysis of the basement depth values.

#### **A. 4. Comparisons of Basement Data Sets**

In order to compare the data sets mentioned above, we performed statistical correlation calculations among the data sets. Table 2 shows the correlation coefficients for each data pairs. The highest correlation is between the UCSD and CRUST 5.1 models. The lowest correlation is between the Cornell and IPE basement data sets. The high correlation between CRUST 5.1 and UCSD models is likely to be a function of the underlying data used in each model. Since the CRUST 5.1 model has low resolution, this correlation is almost meaningless. In the following sections, we analyze each data set against the others and try to bring some constraints on which ones are more reliable.

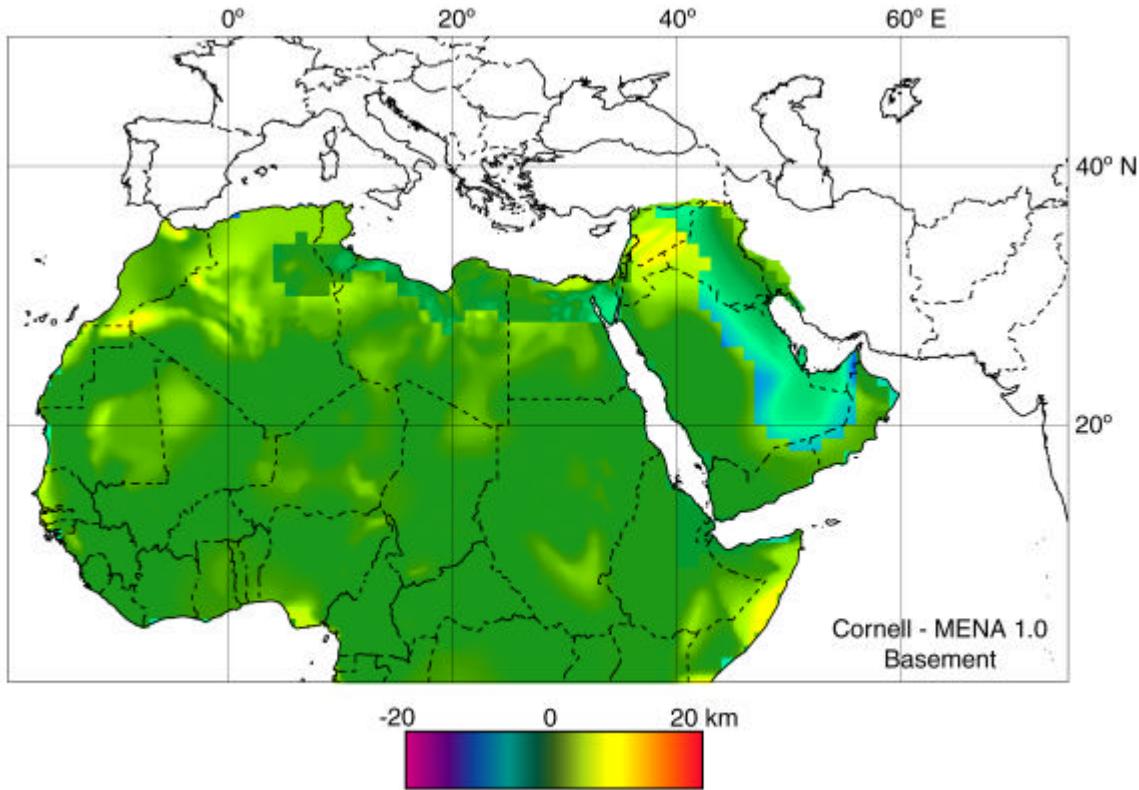
**Table 2.** Correlation Matrix for Basement Data Sets

	<b>Cornell</b>	<b>MENA 1.0</b>	<b>UC</b>	<b>IPE</b>	<b>CRUST 5.1</b>
<b>Cornell</b>	1.00000	0.42071	0.47555	0.28747	0.35394
<b>MENA 1.0</b>	0.42071	1.00000	0.60434	0.55753	0.56240
<b>UC</b>	0.47555	0.60434	1.00000	0.56820	0.63596
<b>IPE</b>	0.28747	0.55753	0.56820	1.00000	0.47460
<b>CRUST 5.1</b>	0.35394	0.56240	0.63596	0.47460	1.00000

#### **- Cornell vs. MENA 1.0 basement maps**

Figure 3 shows the difference map between these two data sets. These two data sets differ strongly in the Arabian peninsula, except in the shield region. The two deep basins in the northern Arabian peninsula, in the Palmyrides and the Rutbah regions, are absent from the MENA 1.0 data set. Similarly, the depth to basement in the Mesopotamian foredeep also shows variations. Since the gradual thickening of the sediments from the shield region to the Zagros is not represented in the MENA 1.0 data set, basement depth variations in this region reach 10 km. Other basins in Africa are also oversimplified in the MENA 1.0 data set and several kilometer thick basins are not adequately represented in the MENA 1.0 data set. This results in the differences seen between these two data sets. The variations in basement depth values mostly range from -2 km to about 6 km.

There are also larger variations in the data sets but with fewer occurrences.



**Figure 3.** Map showing the differences between the Cornell basement model and MENA 1.0 model.

#### ***Comparisons of Other Basement Data Sets***

The overlap between the IPE and Cornell basement maps is quite limited. However, in regions where they do overlap the variations between the two data sets are within  $\pm 2$  km. The variations are mostly at shorter wavelength scales. Important basins, such as the Rif basin in northern Morocco and the deep sedimentary rocks in Syria, are not represented in the IPE data set.

The Cornell and UCSD basement data sets are reasonably well correlated. Most of the basement depth values agree within about two kilometers in these data sets. However, in some cases they disagree about the depth of these basins. Extreme variations reach a value as high as 12 km at locations.

The differences in basement depth values between the Cornell and CRUST 5.1 data sets are due to large cell size of the CRUST 5.1 basement model. It is practically impossible to have a meaningful comparison between these two data sets due to cell size variations.

The MENA 1.0 and IPE basement maps vary strongly. The largest variations are observed in the Caspian Sea and the western Mediterranean Sea regions. The magnitude of these variations reaches 20 km. The basement depth in the Caspian Sea basin is under-estimated by the MENA 1.0 model, and it is overestimated in the western Mediterranean region relative to the IPE data set. Other regions of significant deviations in these data sets are in southern Cyprus, central Arabia, and the Adriatic Sea regions.

There are quite large variations between the MENA 1.0 and UCSD basement data sets in the Caspian Sea and western Mediterranean Sea regions. Significant variations are also observed in central Africa where deep basins exist. The differences are related to the same problem of generalization as in the MENA 1.0 data set. Within a tectonic unit depth-to-basement values vary quite significantly, and these are not accounted for in the MENA 1.0 data set. The UCSD data set does take into account variations within tectonic units with about 100 km resolution.

The differences between the MENA 1.0 and CRUST 5.1 show that in the Mediterranean and eastern Arabia regions basement depth values exhibit large variations. The overall variations are within the  $\pm 5$  km limits. However, in the Mediterranean Sea region and Arabia these differences reach 20 km.

The variations between the IPE and UCSD data sets are seen in the Caspian Sea region and near the Zagros fold belt, the western coast of Africa, and the southern Aegean Sea. The differences reach 20 km in some of these regions.

The IPE and CRUST 5.1 basement maps show the variations mainly due to the aforementioned problem of large sampling size in the CRUST 5.1 model. The variations reach large magnitudes, in several regions, such as the Caspian Sea, they reach high values.

The largest differences between the UCSD and CRUST 5.1 data sets are seen in the Caspian Sea and Black Sea areas. The majority of difference values are within  $\pm 5$  km of each other. The difference map shows numerous smaller regions where significant deviations exist in the basement depth values. This is also simply related to the large sample size in the CRUST 5.1 data set.

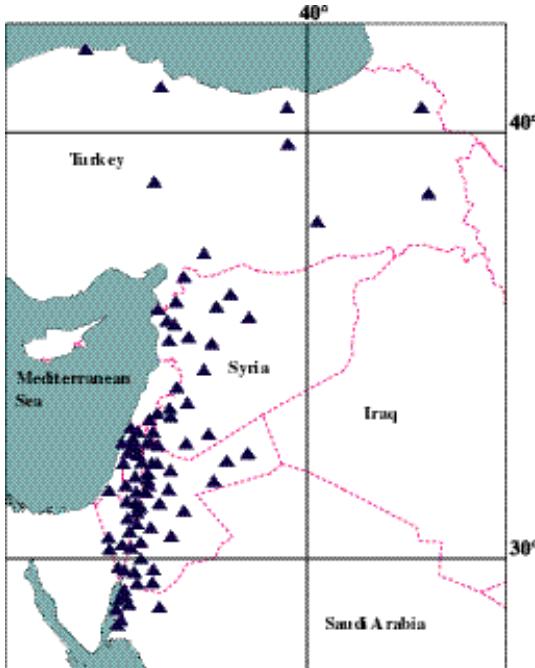
## B. WORK IN PROGRESS

### Seismic Velocity in the Middle East

Currently our efforts are focused on developing a detailed velocity structure for the Middle East region. We are utilizing local seismic networks in Turkey and Syria and make phase readings on digital short period station recordings. These data will then be merged with the ISC catalogue readings and a detailed phase reading database will be developed. These data then will be used to obtain an accurate and detailed velocity structure for the Middle East region. Figure 4 shows seismic stations used in Turkey and Syria along with other stations that report seismic phase readings to ISC.

### Acquiring Ground Truth for Seismic Discrimination

Another effort that is currently underway is to develop a ground truth database using high resolution satellite imagery. Based on collaborations with the LLNL research group, recently we ordered four Landsat 7 TM scenes in Syria, Jordan, and Iran. We will register these TM scenes and determine mining sites within them and their location to be used in LLNL's discrimination efforts.



**Figure 4.** Map showing seismic stations in Turkey and Syria along with stations that report to ISC in the Middle East region.

## CONCLUSIONS AND RECOMMENDATIONS

Our efforts under this Cooperative Agreement are of direct relevance to the comprehensive development of the DOE Knowledge Base. It is essential to provide the Knowledge Base with the most accurate available information; but also, as important, to compare and contrast the final selection of data sets with other data sets available and widely used by researchers in the CTBT community. The revised Cornell basement and Moho depth data sets that we have recently delivered to DOE/LLNL is the most complete and accurate for the Middle East and North Africa regions.

Beyond the scope of this ongoing Cooperative Agreement, we recommend that a second agreement be negotiated between Cornell and DOE in order for Cornell to provide DOE labs with “ground truth” information (based on data available at Cornell) to better strengthen and expand the ongoing calibration efforts in the Middle East and North Africa regions.

## REFERENCES

- Khair, K., and G. N. Tsokas, Nature of the Levantine (eastern Mediterranean) crust from multiple-source Werner deconvolution of Bouguer gravity anomalies, *J. Geophy. Res.*, 104, 25,469-25,478, 1999.
- Mooney, W.D., G. Laske, and T.G. Masters, CRUST 5.1: A global crustal model at 5°x5°: *J. Geophy. Res.*, 103, 727-747, 1998.
- Makris, J., Geophysical and geodynamic implications for the evolution of the Hellenides, *Geological evolution of the Mediterranean Basin, Advanced Research Institute conference on the Geological evolution of the Mediterranean Basin Conference. Sicily, Italy: Nov. 19-27, 1982*, 231-248, 1985.
- Nicolich, R., Crustal structures from seismic studies in the frame of the European geotraverse (southern segment) and crop projects, *The lithosphere of Italy: Advances in earth science research*, Edited by A. Boriani, M. Bonafede, G.B. Piccardo, and G.B. Vai, 41-61, 1989.
- Sandvol, E., Dogan Seber, Alexander Calvert, and Muawia Barazangi, Grid search modeling of receiver functions: implications for crustal structure in the Middle East and North Africa, *J. Geophy. Res.*, 103, 26,899-26,917, 1998a.

- Sandvol, E., Dogan Seber, Muawia Barazangi, Frank Vernon, Robert J. Mellors,, And Abdullah M. Al-Amri, Lithospheric seismic velocity discontinuities beneath the Arabian Shield, *Geophysical Research Letters*, 25, 2,873-2,876, 1998b.
- Sweeney, J., and B. Walter, Preliminary Definition of Geophysical Regions for the Middle East and North Africa, LLNL report # UCRL-ID-132899, 1998.
- van der Beek, P. A., and S. Cloetingh, Lithospheric flexure and the tectonic evolution of the Betic Cordilleras (SE Spain), *Tectonophysics*, 203, 325-344, 1992.
- Vidal, N., J. Gallart, and J. Danobeitia, A deep seismic crustal transect from the NE Iberian Peninsula to the western Mediterranean, *J. Geophys. Res.*, 103, 12,381-12,396, 1998.
- Yarmolyuk, V.A., and Y. Y. Kuznetsov, Geological Map of Africa, 1:5,000,000 scale, Ministry of Geology of the USSR, 1977.
- Yegorova, T.P., V.I. Starostenko, V. G. Kozlenko, and N.I. Pavlenkova, Three-dimensional gravity modelling of the European Mediterranean lithosphere, *Geophys. J. Int.*, 129, 355-367, 1997.